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The nitrogen fertilizer replacement values of incorporated legumes residue to wheat on vertisols of the Ethiopian highlands

Hailu Regassa *, Eyasu Elias, Meron Tekalign, Gudina Legese

Collage of Natural and Computational Sciences, Center for Environmental Sciences, Addis Ababa University, Addis Ababa, Ethiopia

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A B S T R A C T

Soil fertility depletion and continuous cereal cropping are reducing crop production in Ethiopia. Integrated Soil Fertility Management (ISFM) is a good approach for resource-poor farmers because ISFM can help reduce the need for inorganic fertilizer by increasing nitrogen (N) availability in the soil. The study aimed to investigate the effect of preceding crops, legume residue management practices, and N levels on wheat planted. The experiment was set up using a split plot in a randomized complete block design with three replications. The N fertilizer replacement value method was used to estimate the N contribution of legumes to a succeeding wheat crop. The results showed that grain yield and N uptake of wheat crops varied in response to N fertilizer, legume residue management treatments, and tillage practices. Legume residue incorporation positively influenced the agronomic parameters of wheat compared to teff and fallow wheat rotations. The average N fertilizer replacement value from legume rotation was 18–46 kg ha^{-1}. This study showed that a one-year legume-in-biannual wheat rotation is preferable to lying bare fallow during the cropping season. Nevertheless, drainage during legume and wheat cropping is a condition for providing full positive impacts.

1. Introduction

Smallholder farmers are the primary food producers in Sub-Saharan Africa (SSA), where climate change, soil degradation, and mismanagement of agricultural lands are challenging sustainable crop production [1,2]. The soils have lost their natural fertility, and organic matter is depleted, causing aggravated food insecurity and poverty [3,4]. Given that low soil fertility is the major crop production constraint for substance-oriented smallholder farmers, several researchers in the field of soil fertility have proposed ISFM for such environments [3–5]. Integrated Soil Fertility Management (ISFM) is an approach that aims to improve soil fertility and crop productivity through the combined use of organic and inorganic nutrient sources. Integrated Soil Fertility Management (ISFM) is an approach that aims to improve soil fertility and crop productivity through the combined use of organic and inorganic nutrient sources. ISFM is important because it can improve soil health, increase the availability of nutrients and soil organic carbon, help increase crop yields, reduce the environmental impact of agriculture, and also be a promising opportunity for sustainable crop production [5–7]. Legumes can fix atmospheric N and are essential in ISFM because they provide organic resources, alleviate soil constraints by improving soil fertility and fertilizer uptake, and suppress weeds [8]. Among others, legumes play a significant role in crop rotation with cereals since they assist poor resource farmers in reducing inorganic fertilizer use, which is constantly increasing [7]. Particularly deep-rooted legumes have access to deep residual soil N and increase the amount of N available to successive shallow-rooted crops [9].

* Corresponding author.
E-mail address: hailu.regassa@aau.edu.et (H. Regassa).

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Legumes improve soil fertility and instantly increase the availability of nutrients and soil organic carbon while being environmentally friendly and sustainableParticularly deep-rooted legumes have access to deep residual soil N and increase the amount of N available to successive shallow-rooted crops [9]. Forage legume rotations have benefits beyond just boosting the availability of N but also improving the productivity of the farming systems [10]. Concerns over the increasing cost and environmental impact of high inorganic N inputs have led to a reappraisal of the role of legumes in maintaining soil fertility and in providing environmental and economic benefits [11,12].

Ethiopia is a country in the SSA where substantial land degradation and soil fertility depletion are the result of environmental factors and unsustainable land management practices [13]. Cultivation of steep slopes, deforestation, erosive rainfall patterns, excessive grazing, and a lack of effective conservation measures cause land degradation [14,15]. Continuous cereal cropping predominates in agricultural practices and significantly worsens soil erosion and soil fertility depletion [13,15]. Legumes are highly recommended as a natural N source for farming systems in Sub-Saharan Africa (SSA), particularly in countries like Ethiopia. These legumes provide essential N for soil health and crop growth, making them valuable in low-input and resource-limited agricultural settings. Additionally, they have the potential to restore organic matter in degraded soils [1]. Legume leftovers provide N to future crops in the short term and contribute to long-term soil fertility. They do this by promoting the growth of beneficial microorganisms, recycling nutrients, and helping to maintain or increase soil organic matter [16]. Thus, the identification and recommendation of techniques that are both environmentally friendly and produce acceptable crop yields in a sustainable and profitable manner is important for crop production in order to meet the current increase in demand for food. Management practices are the major drivers of sustainable farming because they can modify soil quality through improvements in soil physical, chemical, and hydrological properties. Thus, agricultural practices that conserve natural resources without compromising yields and depend less on inorganic fertilizer are at the center of sustainable agriculture.

Although chemical fertilizer applications increase crop yields, Ethiopian farmers use below-optimal rates of inorganic fertilizers due to a lack of resources and a shortage of cash. Therefore, farmers grow grain legumes after two to three years of continuous cereal cropping. Crop-livestock integration plays an essential role in farming systems because it consists of a range of resource-saving practices that favor the efficient recycling of natural resources by creating a beneficial synergy between crop and livestock production, thus using the outputs of one system as inputs or resources for the other system. The effects of preceding crops, tillage practices, rotation, N application, and crop residue management can be an important venture for low-input agriculture like Ethiopia because the soils are inherently low in soil fertility status. In addition to soil degradation, suboptimal fertilizer application, soil and water erosion, and drought are undermining sufficient crop production. In particular, vertisols are soils that face physical constraints and suffer from soil and water erosion, resulting in reduced crop yields and trapping smallholder farmers in a vicious cycle of poverty. Thus, the identification and recommendation of techniques that boost crop production in a sustainable and profitable manner without affecting the environment is important for this environment in order to meet the current increase in demand for food. Sustainable farming preserves soil quality and protects the environment from adverse effects. Management practices are the major drivers of sustainable farming because they can modify soil quality.

The low system productivity created a competing interest between soil fertility, livestock feed, and household energy requirements. Crop residues are used for livestock feed, while manure is used to fulfill household energy requirements [17]. The legume stover is uprooted at harvest, and hence there is little or no N buildup in the soil to assist the following cereal crop [18]. The legume stover is uprooted at harvest, and hence there is little or no N buildup in the soil to assist the following cereal crop [19]. The benefits of legumes for this farming system in terms of N availability, environmental sustainability, and a pollution-free environment are a priority when considering legumes in cropping systems. Incorporating legumes into crop rotations can help improve soil fertility and reduce the need for synthetic fertilizers. Legumes are known to fix atmospheric N into the soil through their root nodules, which can be used by other crops in the rotation. For low-input agriculture like Ethiopia, where the majority of farmers are economically poor to purchase the ever-increasing inorganic fertilizers, low-cost agricultural technologies that increase soil fertility, reduce soil erosion, are environmentally acceptable, and increase crop productivity are paramount [20]. The advantages of legumes in the cropping system are explained in terms of direct N transfer, residual fixed N, nutrient availability and uptake, effect on soil properties, breaking of pests' cycles, and enhancement of other soil microbial activity [21]. The best benefits from legumes and the biological nitrogen fixation (BNF) system can be utilized by integrating them into cropping systems. In a legume-based BNF system, nutrients are transferred from legumes to cereals through the decomposition and mineralization of legume residues [9,22]. Legume residues are a better source of mineral N for succeeding crops than cereal residues. This is because legume residues have a relatively high N content and a relatively low C: N ratio compared to cereal residues. Given the growing concern for the sustainability of the highland farming system, this study has been initiated, giving due emphasis to tillage practices, residue management treatments, and better crop rotations. The study aims to enhance and conserve soil fertility, which is vital for farm productivity among smallholder farmers. The study will help smallholder farmers improve their crop yields and income by providing them with information on how to improve soil fertility and increase crop yields. For resource-poor farmers, ISFM is a good option because crop rotation or legume residue incorporation can help reduce the inorganic N fertilizer needs of the subsequent crop due to the increased availability of nutrients.

Vertisols cover approximately 7.6 million hectares of land in the Ethiopian highlands. Cereal-based cropping systems are the dominant farming system in the vertisols of the Ethiopian highlands. These soils are prone to land degradation and soil fertility losses due to environmental factors and mismanagement of agricultural lands. When wet, it becomes plastic, sticky, and waterlogged; when dry, it shrinks, and wide cracks open down the profile, limiting the use of conventional farming equipment [23,24]. Climate change and rainfall variability [25] adversely affect tillage practices under traditional farming systems and contribute to low crop production [26,27]. In addition to drainage improvements, vertisols are poor in available plant nutrients due to their physical limitations. In this connection, to overcome the prevailing situations, the use of both organic resources and a reasonable quantity of chemical fertilizers may help poor resource farmers reduce the high cost of chemical fertilizers to be purchased. The inclusion of legumes in systems based on cereals is a crucial alternative to increasing soil fertility and crop productivity. In particular, vertisols constrain crop yields and expose smallholder farmers to a vicious cycle of poverty due to soil and water erosion impacting them and reducing crop productivity. However, we lack information regarding legume residue incorporation and the N transfer to subsequent crops under vertisol conditions in Ethiopia. Therefore, the aim of this study was to evaluate the N fertilizer replacement values of incorporated legume residues and the N contribution to subsequent wheat crop yields in vulnerable agroecosystems facing challenging conditions in the central highlands of Ethiopia.

2. Materials and methods

2.1. Description of the study site

The experiments were conducted at the Holeta Agricultural Research Center, located at 9° 02′ 60″ N, 38° 29′ 59″ E, and at an altitude of 3800 m above sea level in the central highlands of Ethiopia, some 35 km west of Addis Ababa. The four months of the growing season rainfall (June–September) varied considerably for the three-year experimental period: 655, 509, and 755 mm for 2019, 2020, and 2021, respectively (Fig. 1). The 35-year mean rainfall of the growing period for the study area is 768.2 mm. The trend shows that rain for the experimental periods was lower than the long-term mean and showed high variability. The mean monthly minimum and maximum air temperatures for the study periods ranged between 5 °C to 12 °C and 22 °C–28 °C, respectively.

2.2. Soil sample collection and analysis

Prior to establishing the wheat experiments, soil samples were collected from each treatment under legumes and teff plots of both tillage practices. Soil samples were taken randomly from each treatment at three specific depths (0–20 cm, 20–40 cm, and 40–60 cm) using an auger. Each depth of the treatment was replicated three times. One composite sample was created from each depth by thoroughly mixing the collected replicate samples. A total of 36 composite soil samples, 18 from each tillage practice, were sent to the Holeta Agricultural Research Center soil and plant nutrition laboratory for the determination of soil properties. Soil properties were determined on an air-dried base, sieved with a 2-mm mesh. We analyzed the total N using the micro-Kjeldahl method [28] total phosphorus by Bray II [29], particle size distribution using the hydrometer method [30], and organic carbon by Walkley and Black [31]. The simple barium chloride method was used to determine cation exchange [32]. The physical and chemical characteristics of the soil showed an average of 0.8 % total N, 0.97 % organic carbon, 10.4 P (Bray, mg kg^{-1}), and a pH of 5.9 (1:2.5 soil: water). Low infiltration rates, poor permeability, waterlogging, and low availability of nutrients are the major crop production constraints on this soil. The soil of the study site is clayey, an average of 65 % clay, and classified as pellic vertisol [33]. The pH of the soil increases as total N and organic matter decrease with depth. The P status is low in the top 0–60 cm but tends to increase with depth.

2.3. Experimental design and treatment arrangements

The wheat experiments were conducted on plots of land that had previously been planted with legumes and teff, using BBF and camber bed tillage practices, along with the application of P fertilizers. The results of this study were published in Heliyon [34]. Upon reaching maturity, the legumes were either removed, incorporated, or retained on the plots to be used as a treatment during wheat planting. Then, the wheat experiments were established on these tillage practices by dividing the legume plots into six subplots. Wheat was planted on sub-plots with three different N rates (N0-control, N1-30 kg N ha^{-1}, and N2-60 kg N ha^{-1}) and three different legume residue management treatments. The legume residue management treatments were: S: legume residue was removed in December and re-applied in April. R: legume residue was retained on the plots and incorporated in April. RS: legume residue was retained, with the same amount as S, from their respective treatments and incorporated in April. The previously planted teff plots and the newly established bare fallow plots were subdivided into three subplots for N fertilizer application only. The schematic representation of the field layout is presented in Fig. 2.

The experiments were designed as a randomized complete block with a split-plot design, replicated three times. The main factor of

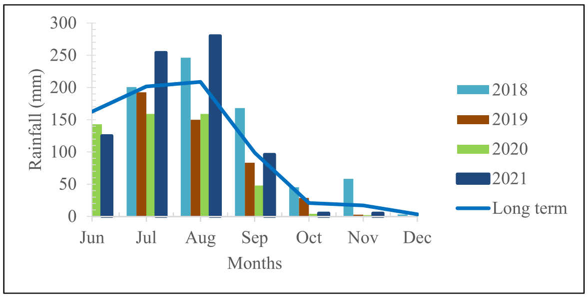

Fig. 1. Seasonal and long-term (35-year) rainfall for the crop growing period (2019–2021) at Holeta.

the experiment was the preceding crops, while the subplot factors consisted of N fertilizer and legume residue management treatments. The wheat variety HAR 1685 was used as the test crop. The experiments were conducted using both tillage practices for two consecutive years (2019–2020). The plot size for the BBF experiment was 7.2 m^2, whereas for the camber beds, it was 6.25 m^2. A summary of the treatment arrangements for wheat planting is provided in Table 1. The wheat planted on BBF and camber beds in 2019 was named Experiment I and II, representing the first series of first-season BBF and camber bed experiments. Similarly, the wheat planted on BBF and camber beds in 2020 was named Experiment III and IV, representing the second series of first-season experiments on BBF and camber beds. The wheat experiments were continued in 2020 and 2021 and were referred to as the second series of second-season experiments.

2.4. Tillage practices

BBF is constructed by attaching a curved metal sheet to both sides of a local plow (maresha). The maresha opens drainage ditches 20 cm in depth, while the metal sheets scope the soil to either side to construct a bed of 80 cm in width when the plowing oxen turn to the other side. The implement constructs raised beds about 80 cm wide, alternating with furrows 40 cm wide and 20 cm deep. The BBF has been constructed annually at the time of crop planting. A tractor-mounted moldboard plow creates camber beds by opening drainage ditches of 50 cm depth and piling the soil to the center, making a concave-shaped bed. Camber beds can have a width of 4–9 m (in the present study, 6 m), the top of which is about 50–60 cm above the bottom of the furrow. The camber bed needs maintenance every three to four years and can serve for several years. We maintained weed-free conditions in the plots by performing hand-weeding. No insecticide or fungicide was applied since there was no outbreak of insects or diseases. Harvesting was done manually using a hand sickle.

2.5. Plant sampling and analysis

At full maturity, the wheat was harvested from 7.2 to 6.25 m^2 of BBF and camber bed tillage practices. Grain and straw yields were determined for each plot. Subsamples were taken to determine grain yield at 12.5 % and dry biomass production by putting them in an oven at 70 °C for 24 h. Sub-samples from each plot were ground to pass through a 2 mm mesh and analyzed for total N in the grain and straw by a micro-Kjeldahl procedure [35]. The harvest index was calculated as the fraction of grain dry matter to total dry matter. The total dry biomass was obtained by summing up grain and straw yields. The various components of fertilizer N use efficiency, namely the N agronomic efficiency (NAE), N recovery efficiency (% NRE), and N physiological efficiency (%NPE), were calculated using Equations (1)–(3) below [36].

$$NAE = (Yf - Y0) / FN \tag{1}$$

$$ANR = 100(NUf - NU0) / FN \tag{2}$$

$$NPE = GY / NU \tag{3}$$

where Yf is the grain dry matter yield of fertilized crops and Y0 is the grain dry matter yield of unfertilized crops, FN is the amount of fertilizer N applied, and NUf and NU0 are the nutrient uptake by fertilized and non-fertilized crops, respectively. Grain yield is the grain dry matter, and NU is the total N uptake. We converted the grain yield to a protein percentage at 12.5 % moisture content by

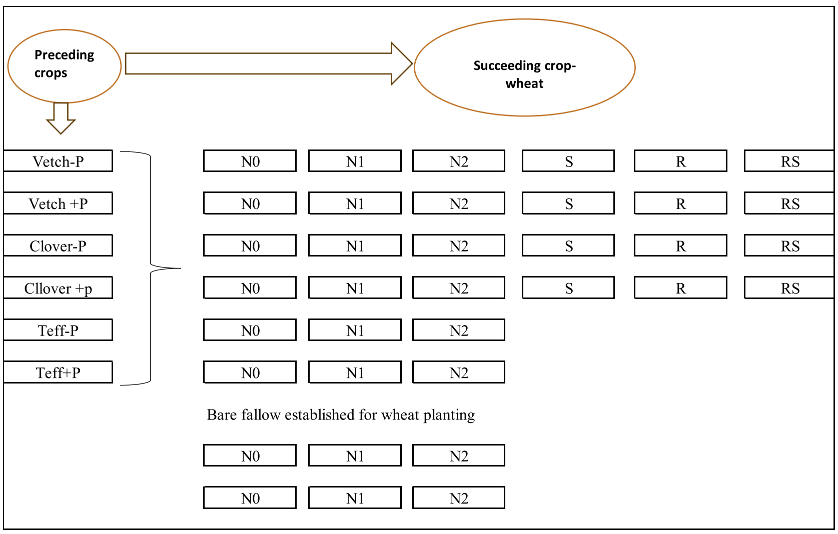

Fig. 2. Schematic representation of experimental treatments.

Table 1
Preceding crops and subplot treatments for wheat planting.

Preceding crops	*Sub treatment	Fertilizer and legume residue N added kg ha^{-1}			
		Experiment I (BBF 2019)	Experiment II (Camber bed 2019)	Experiment III (BBF 2020)	Experiment IV (Camber bed 2020)
Vetch-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	79	135	39	45
	R	72	104	44	23
	RS	144	233	75	68
Vetch + P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	60	184	69	72
	R	174	121	52	26
	RS	120	311	125	79
Clover-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	31	64	11	13
	R	19	62	5	7
	RS	55	120	15	21
Clover + P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	39	93	13	24
	R	29	86	10	11
	RS	66	161	23	34
Tef-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Tef + P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Fallow-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Fallow + P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60

multiplying it by 5.073. We estimated the fertilizer N equivalence from legume rotation by calculating the ratio of the increase in wheat grain yield after legumes without N to the yield increase with 30 kg N ha^{-1} applied after tef or fallow, multiplied by 30 kg ha^{-1}. We calculated the legume N fertilizer replacement factor by dividing the apparent N recovery from legume residue (ANRL) by the apparent N recovery from fertilizer (ANRF) [36].

2.6. Limitation of the study

Research on vertisols has some limitations because it requires a package of technologies to solve crop production constraints under smallholder farmers' conditions. The BBF and camber bed tillage practices help drain excessive rainwater during heavy storms, minimize water stress at critical crop growth stages, and increase crop yields. However, the study didn't consider soil and water erosion and its impact on wheat agronomic parameters due to resource and time constraints, and the tillage practices significantly differ in construction, practical use, and drainage efficiency. Instead, a comparison was made over years for BBF and Camber beds and within years separately for both tillage practices.

2.7. Statistical analyses

An analysis of variance (ANOVA) using Statistics 10.2 (http://statistix.software.informer.com/) software was used to examine the previous crop rotation effects on the subsequent wheat yield, N yields of wheat grain and straw, and tillage practices. We set up the studies using a split plot in a randomized complete block design with three replications. The main-season wheat planted following the harvest of previous crops consisted of three factors: preceding crops: legume species (vetch and clover), teff crops sown with and without P application, and bare fallow. In the experiment, we considered eight preceding crops, applied three N levels (N0-control, N1-30 kg N ha^{-1}, and N2-60 kg N ha^{-1}) as urea after the preceding crops, and used three methods for managing legume residue incorporation (S, R, RS). The ANOVA also included the pooled effect of wheat agronomic parameters for BBF and camber bed tillage practices over the years. The least significant difference (LSD) method was used to compare means. The least significant difference (LSD) in means was used for treatment comparison, and statistical significance was referred to at $P < 0.05$. We conducted regression, correlation, and ANOVA to analyze grain yield, N uptake, N agronomic efficiency (NAE), apparent N recovery (ANR), and physiological efficiency (PE) factors for the various legume residue management treatments and N levels.

3. Results

3.1. Wheat grain yield

A field experiment was conducted on two tillage practices over two years (2019 and 2020) to assess the grain yield of wheat in different treatments, including varied rotation, N rates, legume residue management, and tillage practices. Seasonal variation, rotation, N rates, legume residue management treatments, and tillage practices affected the grain yield of wheat. During 2019, the mean gain yield of wheat on BBF was 1255.3 kg ha^{-1} (95 % CI: 2094.4, 2342.0), while in 2020, this value was 1787.4 kg ha^{-1} (95 % CI: 1620.7, 1954.1). Camber beds in 2019 and 2020 produced a mean grain yield of 1643.1 kg ha^{-1} (95 % CI:1531.6, 1756.3) and 4523.9 kg ha^{-1} (95 % CI: 4242.9, 4804.8), respectively. In both years and tillage practices, the ANOVA showed that year and N treatments had a significant ($P < 0.000$) effect on the grain yield. A combined analysis variance over years for BBF showed that the mean grain yield of wheat was 1460.1 kg ha^{-1} (95 % CI: 1373.1, 1546.9), while for the camber bed, it was 2787.7 kg ha^{-1} (95 % CI: 2576.8, 2998.6). In both years, wheat grain yield was higher on camber beds (1643 vs. 1255.3 kg ha^{-1}) and in 2019 (4312 vs. 1987.4 kg ha^{-1}) than on BBF in 2019 and 2020, respectively. Pooled ANOVA over years for BBF indicated that year and treatments and their interactions significantly ($P < 0.0000$, $F = 19.85$) affected wheat grain yield. The same trend was observed for camber beds, in which wheat grain yield was significantly ($P < 0.0000$, $F = 11.68$) affected by year, treatment, and their interactions. Among the preceding crops, the legume-wheat rotation without N fertilizer applied gave a better wheat yield than the fallow-wheat and teff-wheat rotations. The effect of rotation (preceding crops) on wheat grain yield was more pronounced during the first wheat crop phase, even without N fertilizer application. When rotation and fertilizer application were considered, the highest wheat grain yield was recorded when N was applied at 60 kg ha^{-1} under both tillage practices, followed by N at 30 kg ha^{-1} for all the preceding crops. Wheat planted with N rates following legumes, tef, and fallow rotation showed that the application of N fertilizer increased wheat grain yield by 44 % compared to teff-wheat rotation and a 33 % increase in fallow-wheat rotation. The lowest grain yield of wheat was from teff plots in rotation with wheat (973 kg ha^{-1}).

3.2. Effects of different treatments on wheat yield

The grain yield of wheat in the absence of fertilizer (legume wheat rotation), tef-wheat rotation, and fallow-wheat rotation was highly variable. Preceding crop legumes significantly ($P < 0.05$) enhance wheat grain yield and N uptake compared to teff and bare fallow treatments. The previous crop effect was more pronounced on camber beds than on BBF plots. In the first and second series of first-season experiments, wheat grain yields following legume rotation, particularly vetch, were generally higher than those following tef-wheat. The grand mean of wheat grain yield for non-N applied treatments following legumes, tef, and fallow plots ranged from as low as 0.9 to as high as 3.6 t ha^{-1}. Over the tef-wheat rotation, the percent increase in grain yield of wheat succeeding vetch for non-N-applied treatments ranged from 9 to 44. The clover wheat rotation showed positive and negative values, lacking consistency between seasons and tillage practices. The grain yield advantage of vetch wheat rotation over fallow wheat rotation was 14 % for non-N-fertilized treatments in the first and second series of first-season experiments.

The most consistent effect ($P < 0.001$) was that of N fertilizer, which increased the dry biomass, grain yield, and N uptake of wheat at 60 kg N ha^{-1} (Table 2). However, the interaction effect of the previous crop on N rates was non-significant. The lack of a significant difference between fertilizer applied to the second-season camber bed and BBF is not clear. This may be attributed to the residual effects of legume residue mineralization, seasonal variations, rainfall amount, distribution, and drainage efficiency of the tillage practices. On the other hand, the response of wheat to N fertilizer application varied greatly between seasons and tillage practices. In the first and second series of first-season experiments, the grain yield of wheat ranged from 1.3 to 4.4 t ha^{-1}, while in the second series

Table 2
ANOVA results for wheat grain yield, dry biomass, and N uptake by preceding crops, N fertilizer, and interaction (P-Values).

Wheat agronomic parameters	Source of variations	First and second series first season experiments			
		BBF 2020	Camber bed 2020	BBF 2021	camber bed 2021
Grain yield	Preceding crops	0.014	0.001	0.003	0.001
	N levels	0.001	0.001	0.001	0.001
	Preceding crops * N levels	ns	ns	ns	ns
Dry biomass	Preceding crops	0.014	0.001	0.003	0.001
	N levels	0.001	0.001	0.002	0.001
	Preceding crops * N levels	ns	ns	ns	ns
Total N uptake	Preceding crops	0.003	0.001	0.001	0.001
	N levels	0.001	0.001	0.001	0.001
	Previous crop * N levels	ns	ns	ns	ns

Table 3
ANOVA results for wheat grain yield, dry biomass, and N uptake by preceding crops, N fertilizer, and interaction (P-Values).

Analysis of variance for wheat agronomic parameters (first and second series second season experiments)					
Wheat agronomic parameters	Source ofVariations	First and second series second season experiments			
Grain yield	Preceding crops	0.002	0.001	ns	0.01
	N levels	0.001	0.001	ns	0.005
	Preceding crops * N levels	ns	ns	ns	ns
Dry biomass	Preceding crops	0.001	0.001	ns	0.01
	N levels	0.001	0.001	ns	0.43
	Preceding crops * N levels	ns	ns	ns	ns
Total N uptake	Preceding crops	0.001	0.001	ns	0.004
	N levels	0.001	0.001	ns	ns
	Preceding crops * N levels	0.05	0.003	ns	ns

of first- and second-season experiments, it ranged from 1.5 to 3.0 t ha^{-1}. The average wheat grain yield in BBF in 2020 and 2021 was 2.3 and 3.0 kg ha^{-1}, respectively, during the second season, while it was 1.5 and 1.8 t ha^{-1} on cambered beds in 2020 and 2021. The wheat grain yield was higher in the first season in cambered beds than in BBF, while in the second season, the opposite trend was observed. The grain yield was found to be highly significant ($P < 0.001$) when analyzed against N levels in both seasons of the BBF and camber bed experiments. The R^2 values ranged from 29 % to 79 % over years and tillage practices (Table 4b). The slope of the linear equation revealed that the response of grain to N fertilizer has more of an influence on seasonal variation than on tillage practices. As expected, the teff-wheat rotation showed poor agronomic performance and low grain yield, showing the lowest grain yield and N uptake. Almost comparable wheat grain yield was recorded between legume residue-applied treatments and fallow-wheat roration in the absence of N fertilizer applied, even though leaving the land fallow is not recommended due to environmental reasons.

3.3. Legume residue incorporation and wheat grain yield

The type and amount of legume residue incorporation affected the dry biomass and grain yield, as well as the N uptake of wheat.

Table 4
Regression analysis of wheat grain yield based on legume residue N.

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	32.8	262.6	0.59	27.9	825.2	0.89
Camber bed (Exp. II)	25.6	281.8	0.94	23.7	443.5	0.73
Tillage practices	Second series first season wheat			Second series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. III)	25.7	658.1	0.75	52.7	87.5	0.95
Camber bed (Exp. IV)	2.9	3930.8	0.013	43.4	166.8	0.98

b) Grain vs N fertiliser applied

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	14.7	882.1	0.78	25.3	1579.9	0.79
Camber bed (Exp. II)	13.4	1404.9	0.44	15.9	988.7	0.65
Tillage practices	Second series first season (2020)					
	Slope	Intercept	R^2			
BBF (Exp. III)	20.2	1261	0.54			
Camber bed (Exp. IV)	24.4	3652.7	0.29			

d) Grain yield vs. N uptake for fertilizer applied treatments

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	35.3	237.1	0.96	55.8	23.3	0.96
Camber bed (Exp. II)	25.1	478.8	0.75	38.7	28.7	0.96
Tillage practices	Second series first season (2020)					
	Slope	Intercept	R^2			
BBF (Exp. III)	39.2	203.2	0.92			
Camber bed (Exp. IV)	34.9	812.1	0.82			

The N content of legume residues and legume residue management treatments influenced the grain and dry biomass yield of wheat. The grand mean of wheat grain yield ranged from 1.1 to 4.3 t ha^{-1} for the first and second series of first-season experiments, while for the first and second series of second-season experiments, it ranged from 1.4 to 1.9 t ha^{-1}. Among legume residue management treatments, RS gave comparatively higher wheat yields, followed by R and S. Legume residue management treatments override in wheat grain yield over the no fertilizer application (control) under teff and fallow. ANOVA results showed that the choice of preceding crops and legume residue treatments had a significant ($P < 0.05$) effect on grain and dry matter yields of wheat in 6 out of 8 experiments, however, the interaction of legume residue management treatments with the preceding crops was only significant in two out of eight experiments.

A linear relationship was found between N uptake and wheat grain yields (Fig. 3). The N in the residue of legumes incorporated into the soil varied due to P application. In the first series of experiments, higher incorporation of legume residue had a positive impact on wheat grain yield and showed a significant correlation ($P < 0.05$). Legume residue incorporation significantly affected wheat N uptake, with R2 values ranging from 0.35 to 0.96 over years and tillage practices. A linear relationship and positive correlation were found between residue incorporation of individual legumes and N uptake, with R2 values ranging from 0.56 to 0.97. The slope of the regression equation for N applied in terms of legume residue ranged from 0.5 to 1.4 for Exp. I (first series, first season BBF experiment), while these values ranged from 1.7 to 4 for Exp. III (first series, second season BBF experiment). The slope of the linear regression equation was weak for the first series of the first-season camber bed experiment but tended to be higher (between 0.6 and 3) for the first series of the second-season camber bed experiment.

3.4. Wheat biomass yield, harvest index, and N concentration

Seasonal variations, preceding crops, N fertilizer, and legume residue management treatments positively affected ($P < 0.000$, $F = 13.09$) the dry biomass of wheat. The highest straw yield was recorded at the N rate of 60 kg ha^{-1} followed by 30 kg N ha^{-1}. The straw yield of wheat was not consistent due to the application of different legume residue incorporation treatments. The dry biomass of wheat varied between residue treatments and tillage practices. The rotation effects of legumes, teff, and fallow without N fertilizer application indicated a positive effect when legumes were rotated on straw yield, but the results were non-significant. The significantly highest values were recorded in the treatments where mineral fertilizers were used at either 60 kg N ha^{-1} or 30 kg N ha^{-1}. The lowest ones (ANOVA, $p < 0.05$) were obtained in the unfertilized treatment or non-residue amended treatments. The harvest index (HI) of the dry biomass showed that under both tillage practices and over years, it ranged from 0.38 to 0.42. Regardless of the growing environment, camber beds produced the highest HI (0.42) among the different treatments. The control treatments over the years and under both tillage practices recorded the lowest HI. The ANOVA results showed that treatment had no significant effect on HI in six out of eight experiments. We observed the highest grain and straw N concentrations when there was an interaction between the year and N rate, specifically when 60 kg N ha^{-1} was applied in both growing years. In contrast, the lowest grain N concentration was recorded in the control treatment, which was statistically similar to the grain N content obtained with the N rate of 30 kg ha^{-1} in 2019. As for N level, grain and straw N content increased with increasing N level in both growing years and under both tillage practices, showing the highest values always with the application of the highest N rate (60 kg N ha^{-1}). In general, as compared to 2019, grain and straw N concentrations on both tillage practices increased in 2020, in contrast to 2019.

3.5. Nitrogen uptake of wheat

Similar to grain yields, the N uptake of wheat was affected by preceding crops, the N rate, legume residue, seasons, and tillage practices, but it was not consistent between years and tillage practices (Table 3). The mean total N uptake for the first and second series' first-season wheat ranged from 29 kg ha^{-1} (Exp. I) to 102 kg ha^{-1} (Exp. IV), while for the first and second series' second-season wheat, it ranged from 37 kg ha^{-1} (camber bed) to 41 kg ha^{-1} (BBF). The N uptake of wheat was higher on camber beds than on BBF during the first and second series of first-season experiments, but in the first and second series of second-season crops, it tended to be higher on BBF than on camber beds (Table 3). The mean N uptake for unfertilized plots varied between 19 and 83 kg ha^{-1} for the

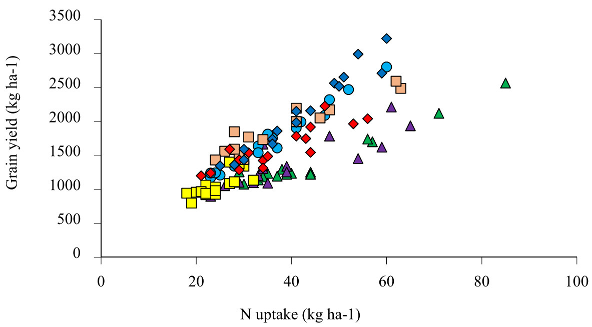

Fig. 3. The relationship between grain yield and N uptake - Exp I, - first series second season BBF, - Exp II, - first series second season camber bed, - second series first season BBF, - second series second season BBF, - second series second season camber bed.

experiments, with the greatest for Exp IV. The values were higher for the first and second series of first-season experiments on camber beds than on BBF. Previous crop treatments were significant in three out of eight experiments, while legume residue-incorporated treatments and N rates showed a significant effect ($P < 0.05$) on total N uptake in all experiments. A significant ($P < 0.05$) effect of the legume residue management treatments (N0, S, R, RS) was evident in the relationship between grain yield and N uptake for the experiments, with R2 ranging from 0.59 to 0.95. For every kg of total N uptake, a wheat grain yield ranging from 24 to 53 kg was obtained.

The relationship between grain yield and N uptake was highly correlated for all the experiments (Fig. 3) and more pronounced in BBF experiments than on camber beds. However, interaction effects were not significant (Table 2). The N uptake of wheat was higher on N-fertilized plots than on legume residue management treatments. The N content of wheat grain following tef-wheat and legume-wheat without N fertilizer declined relative to legume-wheat applied with fertilizer and legume residue N. The pre-wheat legume residue management treatments resulted in varying amounts of N uptake by wheat, with higher values under legume residue treatments that had treatment S and ranged from 18 to 61 kg ha^{-1}. The N uptake of wheat increased in 2020 when wheat was planted during the second season on previously applied legume residue.

3.6. Wheat agronomic parameters relationships

There was a positive correlation between the grain yield of the crop and the total amount of nitrogen uptake from the incorporated legumes. The slope of the linear equation indicates the rate at which the grain yield increased with each additional kilogram of nitrogen uptake from the legume residues. The range of 3–37 kg ha^{-1} suggests that the impact of nitrogen uptake on grain yield varied among different legume species or management practices. The difference may be a combined effect of different factors, such as legume species and legume residue management. The close relationship between grain yield N uptake and the grain yield increase per unit of N uptake after legume treatments explains the positive effects of legume-induced indirect effects. Legume residue incorporated and N fertilizer applied treatments were positively correlated with grain yield and N uptake of wheat (Table 4a–d). The regression analysis shows a strong coherence between the values of dry matter and grain yield of wheat when we consider the R^2 value and the slope of the regression, which are close to one under both tillage practices for Exp I, II, III, and IV. The contribution rate of dry biomass to grain yield was 84 % in Exp. I and 55 % in Exp. II. Correlation analyses showed different relationships between grain yield, dry matter, and HI under different yield levels. For the first series and second season of BBF and camber bed experiments, R^2 was 0.95 and 0.99, $P < 0.001$, respectively. The regression constants for the dry biomass of wheat were higher for camber beds in the first series of second-season experiments of both tillage practices.

3.7. Nitrogen use efficiency of wheat

Seasonal variations and treatment effects had an impact on the N-use efficiency (NUE) of all the components. The interaction of year × N rate revealed a significant effect on agronomic efficiency. The highest agronomic efficiency was obtained from the first series second season (19.8 kg kg^{-1}) and the second series second season (29.4 kg kg^{-1}) wheat experiments at an N rate of 60 kg ha^{-1}. This result shows that BBF agronomic efficiency was higher on BBF than on camber beds over the years. The lowest agronomic efficiency values ranging from 6.2 to 12.2 kg kg^{-1} were recorded on camber beds over the years, which is lower than BBFs in all circumstances. The average values obtained from ANOVA for the NUE parameters indicated that fertilization had a significant and positive influence on all the agricultural components (Table 5). The nutrient efficiency was higher for the inorganic fertilizer than for the N incorporated in terms of legume residues. Averaged over treatments, NAE for the experiments ranged from 7.2 (Exp. II) to 16.3 kg ha^{-1} (Exp. III) for the first and second series of first-season experiments. These values were between 6.2 and 29.4 kg ha^{-1} for the first and second series of second-season wheat experiments, respectively. The NAE tended to increase for the second-season experiments compared to the first-season experiments, except for the second-series camber bed experiment. Wide variations were observed for ANR between seasons and tillage practices. The mean ANR ranged from 0.22 to 27 over seasons and tillage practices for the first and second series of first-season wheat, while for the first and second series of second-season wheat, it ranged from negative to 0.11 to 0.35, with higher values for BBF experiments. PE varied widely between tillage practices and between seasons, with values ranging from negative to 63 kg ha^{-1}.

Table 5
Grand means across treatments for the NAE (kg kg^{-1}), ANR (%) and PE (kg ha^{-1}) for wheat experiments.

Tillage practices	First series first season (2019)			First series second season (2020)		
	NAE	ANR	PE	NAE	ANR	PE
BBF (Exp I)	10.3	0.26	50	19.8	0.35	−60.3
Camber bed (Exp II)	7.2	0.22	77	8.4	0.2	23.2
	Second series first season (2020)			Second series second season (2021)		
	NAE	ANR	PE	NAE	ANR	PE
BBF (Exp III)	16.3	0.27	63	29.4	0.11	47.7
Camber bed (Exp IV)	12.2	0.29	18.8	6.2	0.12	−41

*NAE, ANR, and PE denotes N agronomic efficiency, apparent N recovery, and physiological efficiency, respectively.

4. Rotation benefit and N fertilizer equivalence of legumes

Both rotation benefit and N fertilizer equivalence are important concepts in agriculture as they contribute to sustainable farming practices, efficient nutrient management, and improved crop production. With no-N- applied, the mean grain yield of wheat following legumes ranged from 932 to 1439 kg ha^{-1} for the experiments. The mean values for tef-wheat and fallow-wheat rotations without N application were 924 and 1489 kg ha^{-1} for fallow and between 713 and 1372 kg ha^{-1} for tef. Based on this and the response to 30 kg ha^{-1}, the mean fertilizer equivalence of legumes was estimated, and the values ranged from 6 to 10 kg N for fallow on BBF plots. The fertilizer equivalence for legume rotation compared with tef rotation ranged from 8 to 19 kg N for the experiments. Higher fertilizer equivalencies were recorded on camber bed plots than on BBF plots kg ha^{-1}.

5. Discussion

The physical characteristics of vertisols, particularly their tendency to become sticky, plastic, and waterlogged when wet and hard and cloddy when dry due to rainfall variability, make vertisols difficult to cultivate under traditional farming practices [37]. These properties restrict nutrient availability and hinder plant growth. The efficiency of any drainage system and crop productivity depends on the rainfall amount, duration, and intensity. In the Ethiopian highlands, where the rainfall is erratic, crop production heavily relies on the drainage efficiency of tillage practices and management options. The challenges of waterlogging and nutrient deficiencies are major constraints on crop production in vertisols. In the Ethiopian highlands, wheat is a crucial food crop that relies heavily on costly inorganic fertilizers. To address this issue, we explored alternative methods to improve soil fertility and increase crop yields. Legumes, known for their nitrogen-fixing abilities, are widely used to restore soil fertility and reduce the need for nitrogen fertilizers. Introducing legumes into cropping systems is seen as a sustainable approach to intensifying agriculture in Sub-Saharan Africa, including Ethiopia [19,38,39]. In this study, camber beds increased the grain yield of wheat, ranging from 24 to 59 % over the years, due to their better drainage efficiency. However, planting wheat on camber beds for two consecutive years following legumes without fertilizer application declined compared to BBF. The wheat grain yield decline in the first and second series of second-season experiments on the camber bed can be explained by the leaching and denitrification of the available nutrients due to higher beds. Drainage is crucial for vertisols, and while improving the drainage system, one has to take caution about soil and water erosion hazards related to improper tillage practices and furrow construction.

Seasonal rainfall amount and distribution, tillage practices, and N fertilizer applied in terms of inorganic fertilizer and legume residue incorporation have a positive impact on wheat grain and dry biomass yield and N uptake. Soils with low organic matter usually do not respond to applied fertilizers due to depleted organic matter [39]. Therefore, the inclusion of legumes in the cropping system is important. In this study, legume-wheat rotation and residue incorporation significantly affected the test crop's grain yield and N uptake. This is in agreement with past studies conducted regarding organic amendments [40,41]. Waterlogging and nutrient deficiencies are the major crop production constraints on vertisols [8,42], coupled with drainage improvement [24,43]. However, while improving the drainage system, one has to take caution about soil and water erosion hazards related to improper tillage practices and during furrow construction.

5.1. Legume-wheat rotation, residue incorporation, and N application

Using organic amendments in low-input agriculture can enhance crop production by reducing the reliance on chemical fertilizers. These amendments release beneficial nitrogen for the subsequent crop while minimizing negative environmental impacts [18,44]. In regions with high rainfall, planting crops during the long rainy season can help conserve soil nitrogen by reducing runoff and leaching from mineral fertilizers. Incorporating legume residue into the soil has been observed to effectively reduce soil and water erosion compared to bare and cereal-cereal rotations. Early planting with improved drainage systems can assist farmers in reducing soil and nutrient loss. Legume-wheat rotation and the incorporation of legume residues can fulfill the nitrogen requirements of subsequent crops through the decomposition and mineralization of legume residues, as well as the soil nitrogen-conserving effect of legumes [40,45]. The lower nutrient export from the soil by legumes and their ability to fix atmospheric nitrogen are additional factors contributing to increased wheat grain yield [45,46]. The response of wheat crops to legume residue nitrogen varies depending on the legume species, management of legume residues, nitrogen content of legumes, and soil nitrate levels at sowing. In the absence of nitrogen fertilizer application, wheat grain yield is typically higher in legume-wheat rotations compared to teff-wheat rotations due to the retention of nutrient inputs in available soil nutrient pools [47,48]. Legumes' capacity to conserve soil N and fix N can enhance wheat grain yield in legume-wheat and tef-wheat rotations compared to non-fertilized legume-wheat. Legumes' capacity to conserve soil N and fix N can enhance wheat grain yield in legume-wheat and tef-wheat rotations compared to non-fertilized legume-wheat. Past studies on rotation, legume residue decomposition, and further mineralization have shown the positive impact of legumes on the subsequent grain yield of crops. Legumes' ability to conserve soil N and their N-fixing capacity can also contribute to increased crop yields [41,48].

Legume-wheat can enhance wheat grain yield through the conservation of soil nitrogen and nitrogen fixation by legumes. Several studies have confirmed the positive impact of legumes on subsequent wheat yield [46,48,49]. Factors such as legume species, carbon-to-nitrogen ratio, residue incorporation methods, soil type, microorganisms, rainfall, and temperature influence the availability of soil mineral nitrogen for the following crops [41]. The presence of inorganic nitrogen in the soil may also affect the mineralization of decomposing agricultural waste. Additionally, timing and losses through leaching, denitrification, immobilization, or volatilization may have influenced the availability of necessary nitrogen concentration from legume residues for wheat crops [50].

It's possible that the necessary N concentration in legume residues was not fully reached at the time when wheat needed more N or that it was lost as a result of leaching, denitrification, immobilization, or volatilization. A comparison made between wheat yield under S and N0 showed that the S treatment gave a higher wheat grain yield because the soil mineral N under legume residue treatments was still sufficient for the yield difference. However, an important observation was that grain yields of wheat under the different legume residue treatments varied widely and lacked consistency concerning the amount of N added in terms of legume residue. These can be related to several external factors such as environmental factors, legume species and, and time and type of legume residue application [50,51].

5.2. Nitrogen uptake and use efficiency

N use efficiency is a crucial parameter in agricultural systems as it reflects the plant's ability to convert absorbed nitrogen into biomass or grain yield. The predominant influence on wheat N uptake was the addition of N fertilizer at a rate of 60 kg ha^{-1}, but this varied between tillage practices [45]. It is reasonable to conclude that N is the main factor limiting crop production in these soils. However, the efficiency of N uptake by wheat grain varied greatly under legume residue management treatments related to legume species difference and the C: N ratio. The residual effect of legume residue was more pronounced on N uptake in wheat when it was planted for the second time [51]. Several studies have shown that applying inorganic N to crops increases NUE because it is immediately available to succeeding crops. However, as N rates rise, cereals' agronomic, physiological, and apparent recovery efficiencies decline [52,53]. However, the N contribution from legume residues is usually released slowly and may be available to the second and third succeeding crops [54]. Based on seasonal variations and tillage practices, the mean NAE ranged from 6.2 to 29.4 kg ha^{-1}. Study conducted on vertisols of Bale highlands in Ethiopia showed that the NUE of wheat for applied N ranged from 9.5 to 18.3 kg ha^{-1} on waterlogged vertisol sites. Several factors may contribute to various NUEs, in particular the availability of moisture, the soil's nutritional status, and its ability to retain nutrients.

5.3. Recovery of residue N

The N recovery from residues in succeeding wheat crops varied widely. Our results showed that the contribution of legume residue N to wheat yield and N uptake was variable based on the amount of legume residue incorporated and legume residue management treatments. The findings are in agreement with previous research [54]. The total N uptake for wheat following legume rotation or residue incorporation had tremendous variations in residue N recovery, suggesting that the influence of residue management treatments was not equal. Comparisons of direct residue N recovery between treatments are the most appropriate way to compare treatments, as varying amounts of N were added as residues. The lack of an appreciable benefit from legume residue incorporation in some cases could be attributed to N losses or may be affected by the timing of incorporation, which was three months before planting wheat for these experiments.

5.4. Fertilizer replacement value

The highest fertilizer replacement value for legumes in this study was much better on camber beds, at about 25 kg of grain per kg N, while on BBF it was between 19 and 23 kg per kg N, varying between seasons and tillage practices. The value is nearly equal to the half-N recommended fertilizer rate for wheat in Ethiopia [55]. However, an actual yield increase of 30 kg N ha^{-1} may not be achievable due to differences in the N sources and some external factors governing the sources. Field conditions are influenced by multiple factors that can counteract the estimation process [56] for this cropping system since several factors counteract field conditions. Several factors can affect the decomposition and mineralization of legume residue, making it challenging to estimate the N balance [57] 59. It would be instructive to look at some of these for further research. The study showed that optimal fertilizer savings were recorded for all treatments, justifying legume residue incorporation as having an advantage. On camber beds, the N fertilizer savings decreased by 50 % compared to BBF plots. This is probably attributed to the leaching of the mineralizable N below the root zone. In the case of 2020, fertilizer savings decreased drastically on BBF, while camber beds showed an increasing trend. The variation in fertilizer N equivalence values can be influenced by factors such as the dependence of legumes on N fixation, the soil mineral N sparing effect, dry biomass production, and the amount of N incorporated from residue sources. Fertilizer N equivalence values for this environment are optimal; even low fertilizer equivalence may help farmers with limited access to commercial fertilizers.

6. Conclusion

From the study, it can be concluded that grain yields of wheat can be maximized with N application rates of 60 kg ha^{-1} which significantly affected all the agronomic parameters. Among the preceding crops to wheat, teff-wheat rotation without N fertilizer application significantly reduced wheat grain yield, while fallow-wheat rotation without applying N comparatively gave better wheat grain yields. The inclusion of legumes in rotation or incorporation into the soil drastically increased the grain yield of wheat. Improved drainage systems helped vertisols respond to added N from legume residue or inorganic fertilizer. In the absence or limited availability of inorganic fertilizers, poor resource farmers can take advantage of growing forage legumes and incorporating residues to replenish the soil with organic matter, which may serve as an essential source of nutrients. Fertilizer N equivalence values for this experiment were minimal. The average N fertilizer replacement value from legume rotation was 18–46 kg ha^{-1}. This study showed that a one-year legume-in-biannual wheat rotation is preferable to lying bare fallow during the cropping season. Nevertheless, drainage during legume and wheat cropping is a condition for providing full positive impacts. For sustainable crop production on vertisols, location-specific agro-climatological studies, tillage practices, and nutrient management are crucially important. Even legumes with low fertilizer equivalence may be of interest to farmers who have limited access to commercial fertilizers.

Data availability statement

The data utilized for this research is accessible at Addis Ababa University and the Ethiopian Institute of Agricultural Research. Upon request, the data can also be provided.

CRediT authorship contribution statement

Hailu Regassa: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eyasu Elias:** Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Meron Tekalign:** Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation. **Gudina Legese:** Supervision, Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:HAILU REGASSA reports financial support was provided by Ethiopian Institute of Agricultural Research. Hailu Regassa reports a relationship with Ethiopian Institute of Agricultural Research that includes: non-financial support. Hailu Regassa, there are no patents to disclose has patent pending to there is no patent right. NO If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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